Hadron collisions:
from the quagmire towards solid ground

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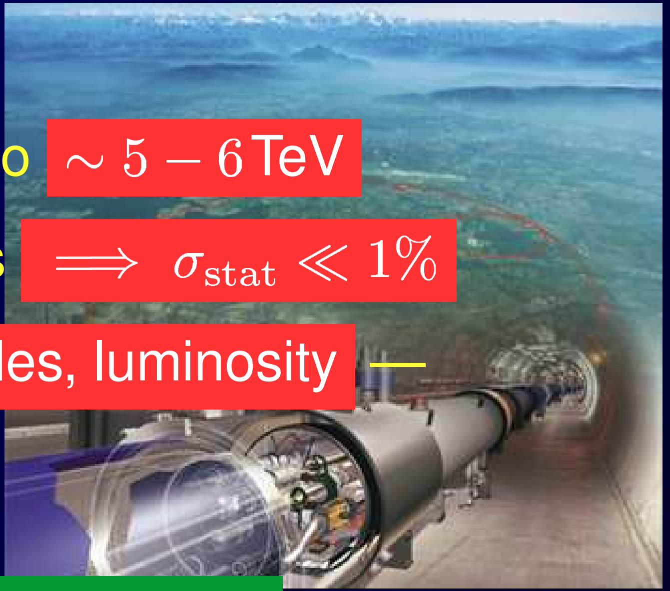
- Matrix Elements and Parton showers
- The Underlying Event
- Beam Remnants and Hadronization

The Near (Accelerator) Future is Hadron Collisions

- **Tevatron**
  - 2 – 10 fb^{-1} by LHC turn-on $\rightarrow$ Large W, Z, and $\mathrm{t\bar{t}}$ samples (including hard tails !)
  - Reduction of t and W mass uncertainties by $\sim 50\%$
  - Potential discoveries...



- **LHC**
  - Explore EWSB / Probe New Physics up to $\sim 5 - 6$ TeV
  - 10 fb^{-1} $\rightarrow$ more than 10^7 W, Z, $\mathrm{t\bar{t}}$ events $\Longrightarrow \sigma_{\mathrm{stat}} \ll 1\%$
  - Improved Systematics — jet energy scales, luminosity — from high–statistics 'standard candles'
- $\Longrightarrow$ Large discovery potential + percent level physics!

Parton Showers: the basics

- Today, basically 2 approaches to showers:
  Parton Showers (e.g. HERWIG, PYTHIA)
  and (dual QCD) Dipole Showers (e.g. ARIADNE).

  Basic formalism: Sudakov (DGLAP) evolution:

$$\mathrm{FSR}: \quad \boxed{\mathrm{d}\mathcal{P}_a = \frac{\mathrm{d}X^2}{X^2}\frac{\alpha_{\mathrm{s}}(X^2)}{2\pi}\,P_{a\to bc}(z)\,\mathrm{d}z\,\exp\left(-\int_X^{X_{\mathrm{max}}}\cdots\right)}$$

  - X: some measure of 'resolution', z: energy sharing
  - $P_{a\to bc}(z)$: collinear limit ($t \to 0$) of ME (can include $m \neq 0$ effects).
  - Resums Leading Logs + some NLL effects ($p_\perp$ conservation, running α_s etc).
  - Big boon: universal and amenable to iteration $\to$ fully exclusive (='resolved') final states $\to$ match to hadronization
  - Depends on (universal) phenomenological params (color screening cutoff, ...) $\leftrightarrow$ determine from data (compare eg with form factors) $\equiv$ 'tuning'
  - Phenomenological assumptions $\leftrightarrow$ some algorithms 'better' than others.

New Parton Showers: Why Bother?

- Today, basically 2 approaches to showers:
  Parton Showers (e.g. HERWIG, PYTHIA)
  and (dual QCD) Dipole Showers (e.g. ARIADNE).
- Each has pros and cons, e.g.:
  - In PYTHIA, ME merging is easy, and emissions are ordered in some measure of (Lorentz invariant) hardness, but angular ordering has to be imposed by hand, and kinematics are somewhat messy.
  - HERWIG has inherent angular ordering, but also has the (in)famous "dead zone" problem, is not Lorentz invariant and has quite messy kinematics.
  - ARIADNE has inherent angular ordering, simple kinematics, and is ordered in a (Lorentz Invariant) measure of hardness, but is primarily a tool for FSR, with somewhat primitive modeling of ISR and hadron collisions, and $g \to q\bar{\mathrm{q}}$ is 'artificial' in dipole formalism.
  - Finally, while all of these describe LEP data very well, none are perfect.
- Possible to combine the virtues of each of these approaches while avoiding the vices?

UE: Present Status

Available tools:

- Soft UE model (min-bias) (HERWIG)
- Soft+semi-hard UE (DTU) (ISAJET, DTUJET)
- Multiple Interactions (PYTHIA, JIMMY, SHERPA)

Of these, the Sjöstrand–van Zijl model (from 1987) is probably the most sophisticated;
(e.g. tunes like 'Tune A' can simultaneously reproduce a large part of Tevatron min–bias and UE data, as well as data from other colliders.)

[T. Sjöstrand, M. van Zijl, "A Multiple Interaction Model For The Event Structure In Hadron Collisions", Phys. Rev. D 36 (1987) 2019.]

[R.D. Field, presentations available at `www.phys.ufl.edu/~rfield/cdf/`]

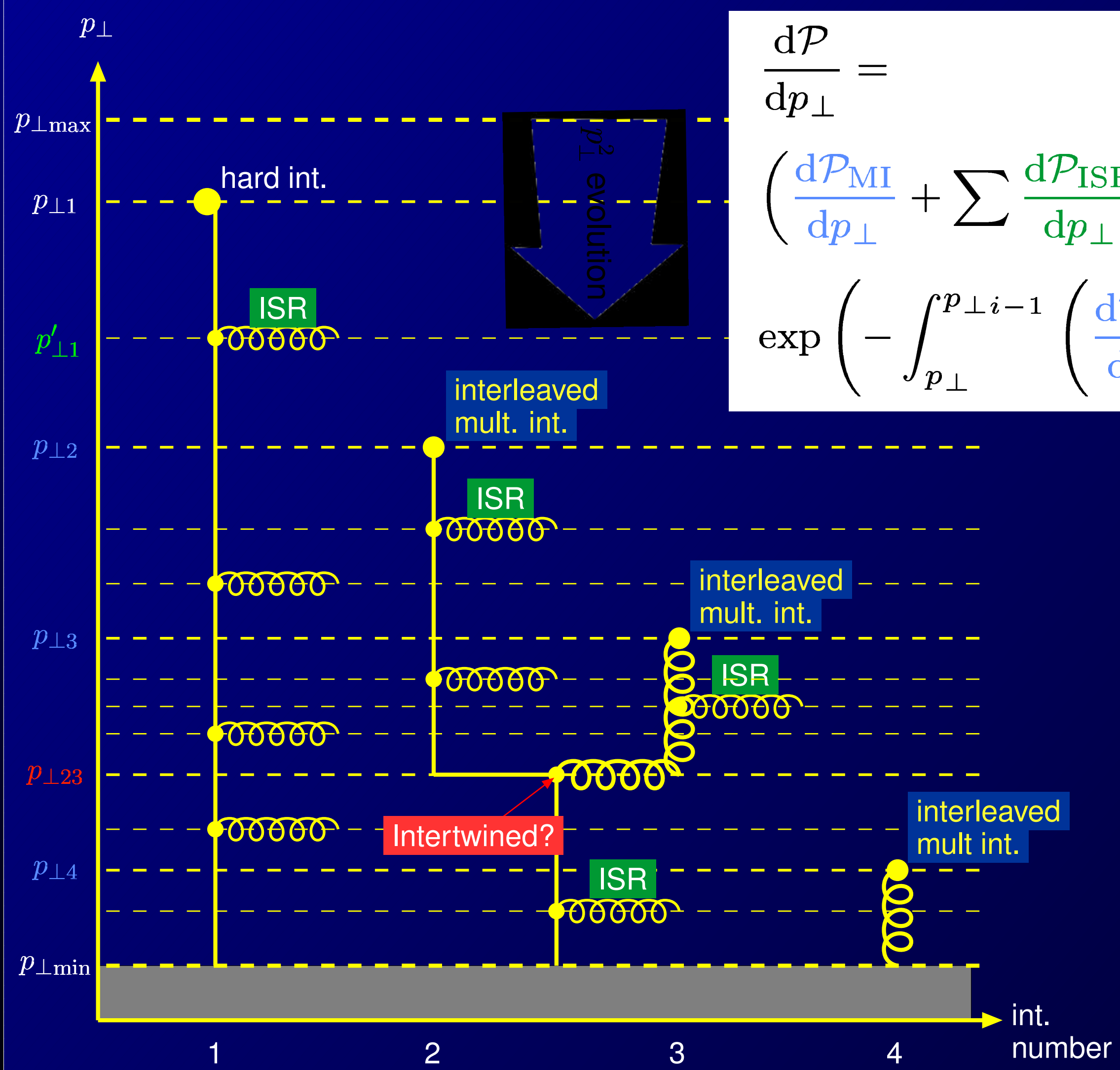
New UE Model: Why Bother?

- QCD point of view: hadron collisions are complex.
  Present models are not.
  More detail $\rightarrow$ more insight $\rightarrow$ more precision
- LHC point of view: reliable extrapolations require such insight.
  Simple parametrizations are not sufficient.
- New Physics and precision point of view: random and systematic fluctuations in the underlying activity will impact cuts/measurements:
  More reliable understanding is needed.

Unifying PS and UE: Interleaved Evolution

The new picture: start at the most inclusive level, $\boxed{2 \to 2}$.

Add exclusivity progressively by evolving *everything* downwards.

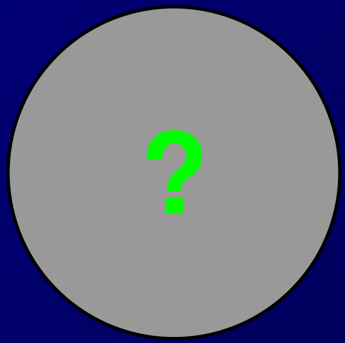


$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_\perp} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{JI}}}{\mathrm{d}p_\perp} \right) \times \exp\left(- \int_{p_\perp}^{p_{\perp i-1}} \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{JI}}}{\mathrm{d}p'_\perp} \right) \mathrm{d}p'_\perp \right)$$

$\sim$ “Finegraining”

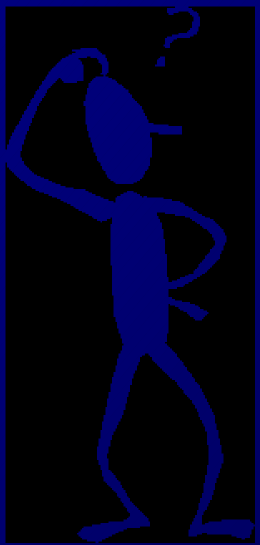
Correlations in flavour and $\mathbf{x}_i$

Consider a hadron, H:



MI context: need PDFs for finding partons $i_1 \ldots i_n$ with momenta $x_1 \ldots x_n$ in H probed at scales $Q_1 \ldots Q_n$

$$f_{i_1 \ldots i_n / H}(x_1 \ldots x_n, Q_1^2 \ldots Q_n^2)$$



But experimentally, all we got is $n = 1$.

Global fits:	CTEQ	MRST	
DIS fits:	Alekhin	H1	ZEUS
Other PDF:	GRV	...	

$$\rightarrow f_{i_1/H}(x_1, Q_1^2)$$

So we make a theoretical cocktail...

Correlated PDF's in flavour and $\mathbf{x}_i$

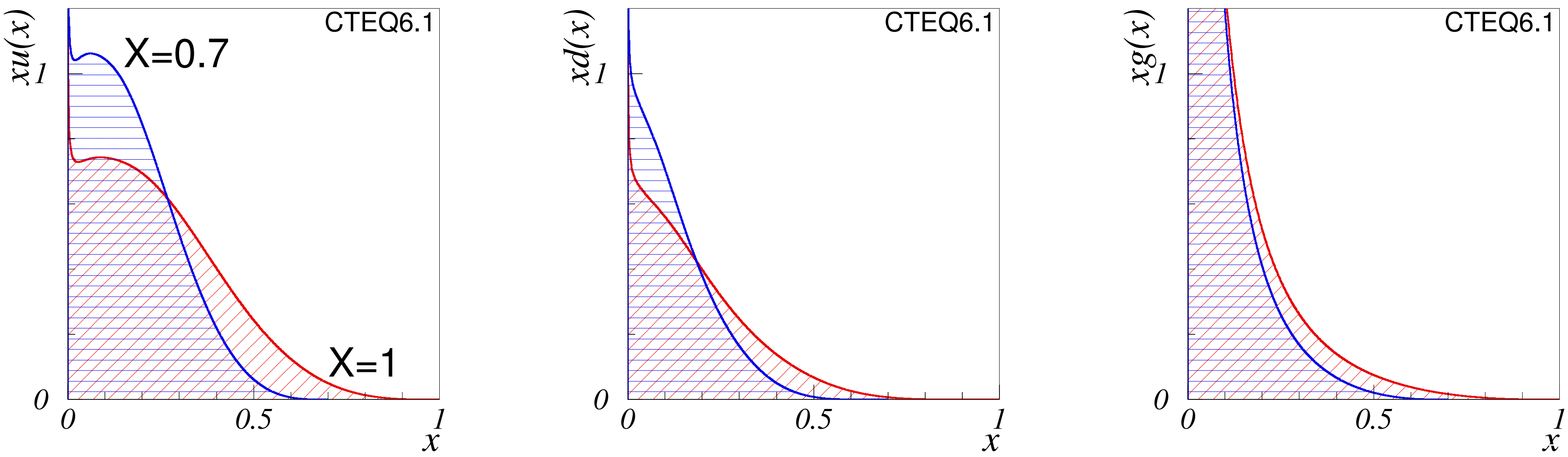
Q: What are the pdf's for a proton with 1 valence quark, 2 sea quarks, and 5 gluons knocked out of it?

1. Overall momentum conservation ('trivial'):

Starting point: simple scaling ansatz in x.

For the n'th scattering:

$$x \in [0, X] \;\; ; \;\; X = 1 - \sum_{i}^{n-1} x_i \implies f_n(x) \sim \frac{1}{X} f_0\left(\frac{x}{X}\right)$$



Correlated PDF's in flavour and $\mathbf{x}_i$

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Normalization and shape:

- If valence quark knocked out.

  → Impose valence counting rule: $\int_0^X q_{fn}^{\mathrm{val}}(x, Q^2)\,\mathrm{d}x = N_{fn}^{\mathrm{val}}$.

- If sea quark knocked out.

  → Postulate “companion antiquark”: $\int_0^{1-x_s} q_f^{\mathrm{cmp}}(x; x_s)\,\mathrm{d}x = 1$.

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→ Postulate "companion antiquark": $\int_0^{1-x_s} q_f^{\mathrm{cmp}}(x; x_s)\, \mathrm{d}x = 1$.

✧ But then **momentum sum** rule would be violated:

$$\int_0^X x\Big(\sum_f q_{fn}(x, Q^2) + g_n(x, Q^2)\Big)\mathrm{d}x \neq X$$

→ Use floating normalization of sea+gluon to ensure overall momentum cons

Correlated PDF's in flavour and $\mathbf{x}_i$

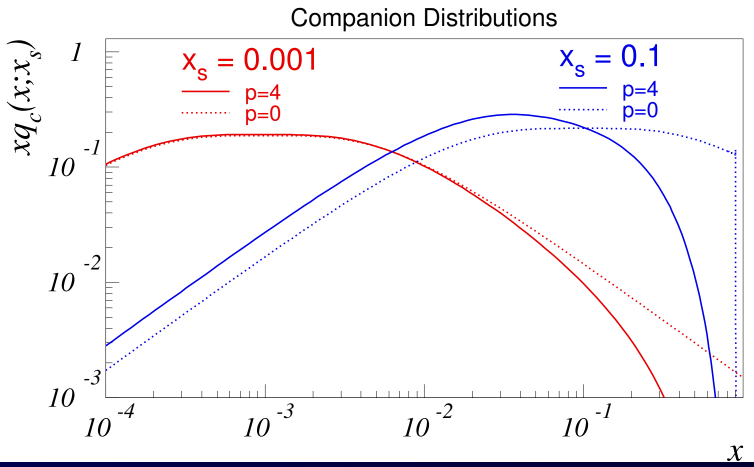
Remnant PDFs

$$\text{quarks}: \quad q_{fn}(x) = \frac{1}{X}\left[\frac{N_{fn}^{\text{val}}}{N_{f0}^{\text{val}}} q_{f0}^{\text{val}}\left(\frac{x}{X}, Q^2\right) + a\, q_{f0}^{\text{sea}}\left(\frac{x}{X}, Q^2\right) + \sum_j q_{f0}^{\text{cmp}_j}\left(\frac{x}{X}; x_{s_j}\right)\right]$$

$$q_{f0}^{\text{cmp}}(x; x_s) = C\,\frac{\tilde{g}(x + x_s)}{x + x_s} P_{g\to q_f\bar{q}_f}\left(\frac{x_s}{x + x_s}\right) \quad ; \quad \left(\int_0^{1-x_s} q_{f0}^{\text{cmp}}(x; x_s)\,\mathrm{d}x = 1\right)$$

$$\text{gluons}: \quad g_n(x) = \frac{a}{X} g_0\left(\frac{x}{X}, Q^2\right)$$

$$a = \frac{1 - \sum_f N_{fn}^{\text{val}}\langle x_{f0}^{\text{val}}\rangle - \sum_{f,j}\langle x_{f0}^{\text{cmp}_j}\rangle}{1 - \sum_f N_{f0}^{\text{val}}\langle x_{f0}^{\text{val}}\rangle}$$



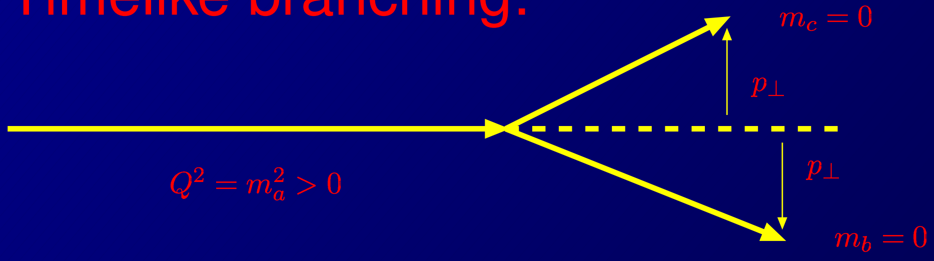
Can be used to select $p_\perp$-ordered set of $2 \to 2$ scatterings, and to perform backwards DGLAP ISR evolution.

$p_\perp$–ordered showers: Simple Kinematics

Consider branching $a \to bc$ in lightcone coordinates $p^\pm = E \pm p_z$

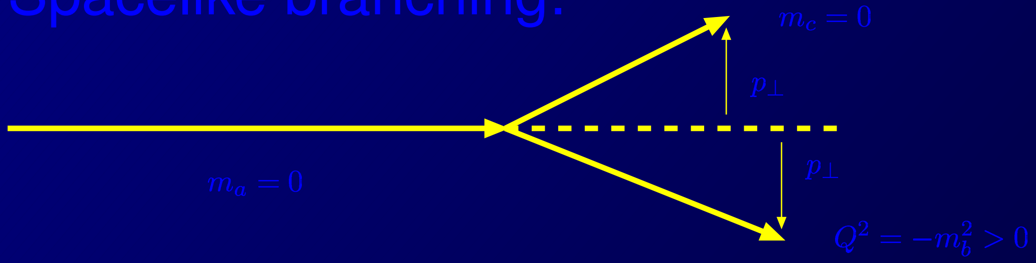
$$\left.\begin{aligned} p_b^+ &= z p_a^+ \\ p_c^+ &= (1-z) p_a^+ \\ p^- & \text{ conservation} \end{aligned}\right\} \Longrightarrow m_a^2 = \frac{m_b^2 + p_\perp^2}{z} + \frac{m_c^2 + p_\perp^2}{1-z}$$

Timelike branching:



$$p_\perp^2 = z(1-z)Q^2$$

Spacelike branching:



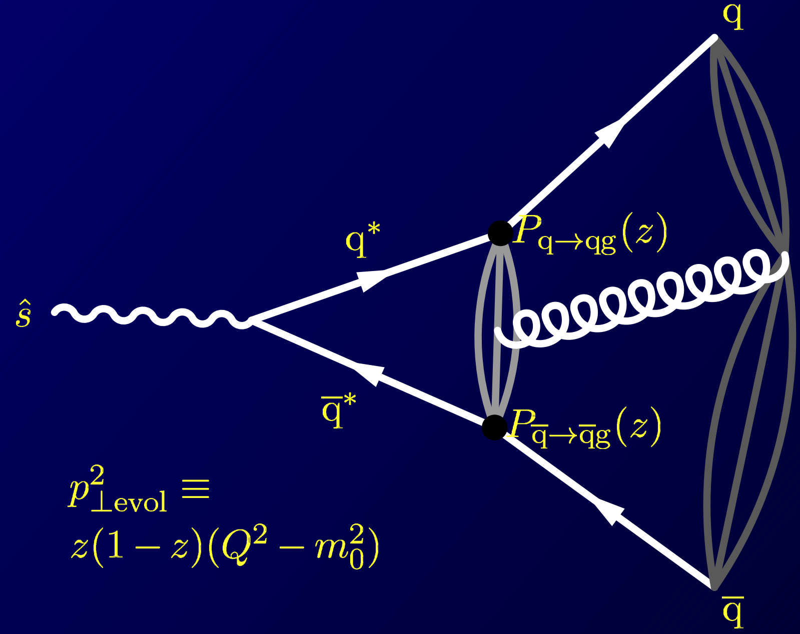
$$p_\perp^2 = (1-z)Q^2$$

(NB: massive evolution and massive splitting kernels used for $m_0 \neq 0$)

$p_\perp$–ordered showers: Kinematics

Merged with X + 1 jet Matrix Elements (by reweighting) for: h/γ/Z/W production, and for most EW, top, and MSSM decays!

Exclusive *kinematics* constructed inside dipoles based on Q^2 and z, assuming yet unbranched partons on-shell



Iterative application of Sudakov factors...

$\Rightarrow$ One combined sequence $p_{\perp\mathrm{max}} > p_{\perp 1} > p_{\perp 2} > \ldots > p_{\perp\mathrm{min}}$

NB: Choice of $p_{\perp\mathrm{max}}$ non-trivial and *very* important for hard jet tail
$\leftrightarrow$ wimpy vs power showers...

$p_\perp$–ordered showers: Kinematics

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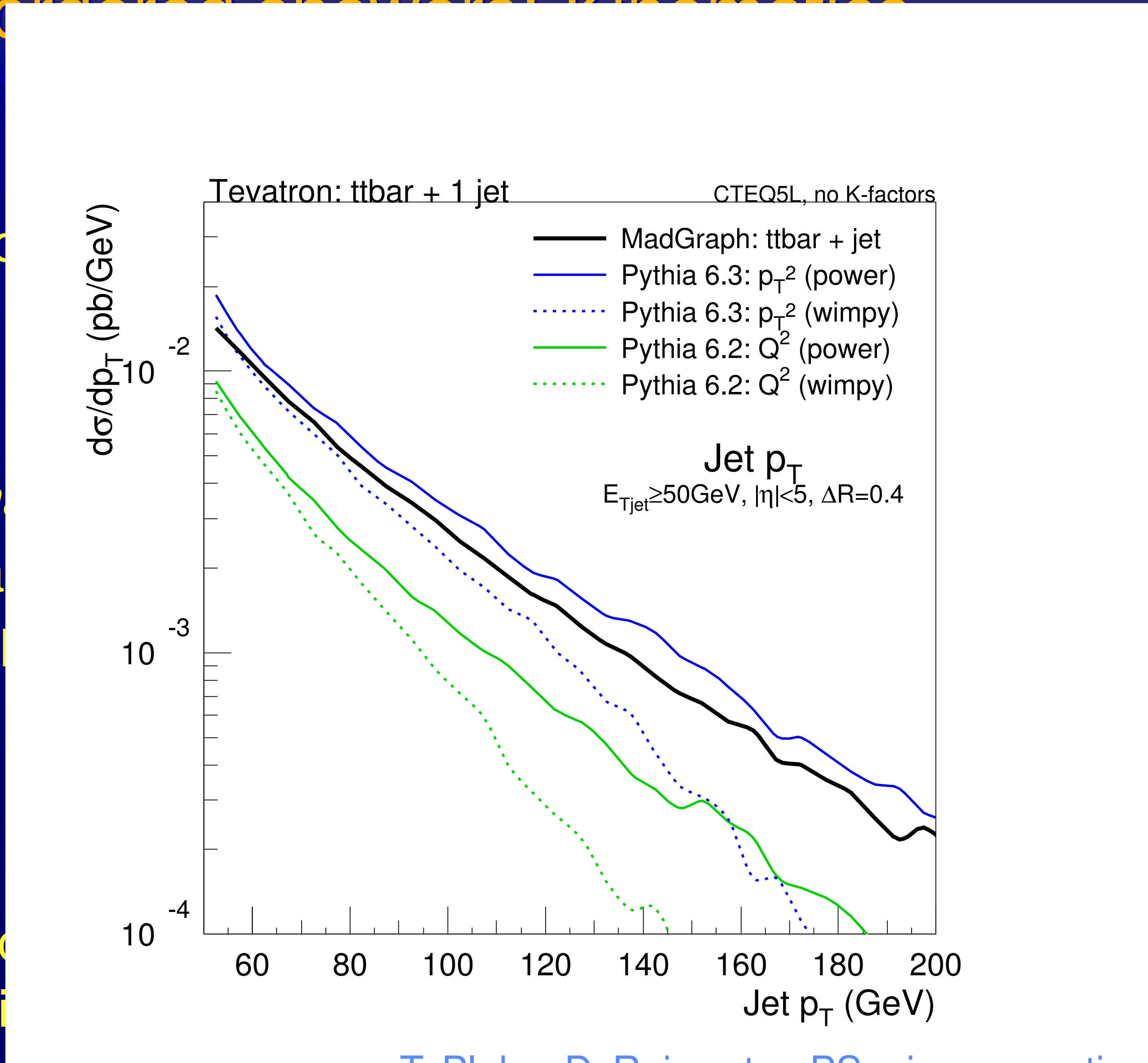

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Model Tests: FSR Algorithm

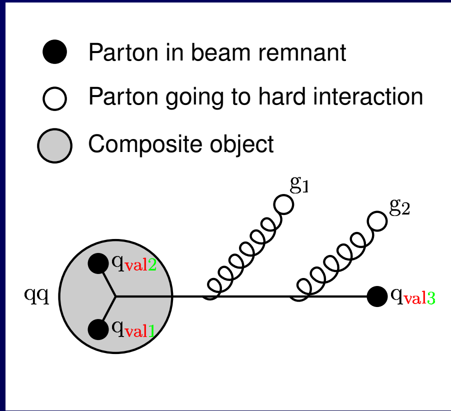
- Tested on ALEPH data (courtesy G. Rudolph).

		$\sum \chi^2$ of model	
Distribution	nb.of	PY6.3	PY6.1
of	interv.	$p_\perp$-ord.	mass-ord.
Sphericity	23	25	16
Aplanarity	16	23	168
$1-$Thrust	21	60	8
Thrust$_{\mathrm{minor}}$	18	26	139
jet res. y_3(D)	20	10	22
$x = 2p/E_{\mathrm{cm}}$	46	207	151
$p_{\perp\mathrm{in}}$	25	99	170
$p_{\perp\mathrm{out}} < 0.7$ GeV	7	29	24
$p_{\perp\mathrm{out}}$	(19)	(590)	(1560)
x(B)	19	20	68
sum $\quad N_{\mathrm{dof}} =$	190	497	765

- (Also, generator is not perfect. Adding 1% to errors $\Rightarrow$ $\sum \chi^2 = 234$. i.e. generator is 'correct' to $\sim$1%)

The Beam Remnant – Fast Forward

- Composite BR systems (diquarks, mesons, w. pion/gluon clouds?) $\rightarrow$ larger x?



- Remnant PDFs (and fragmentation functions) $\rightarrow$ Lightcone fractions $x_{j,k}$ in remnants (with (E,p) conserved)

- Confined wavefunctions $\rightarrow$ Fermi motion $\rightarrow$ $k_\perp = \hbar / r_\mathrm{p} \sim \Lambda_\mathrm{QCD}$.

  Empirically, one notes a need for larger values!

$$\frac{\mathrm{d}^2 N}{\mathrm{d}k_x \mathrm{d}k_y} \propto e^{-k_\perp^2/\sigma^2(Q)} \qquad \begin{array}{r} \sigma(1~\mathrm{GeV}) \approx 0.36~\mathrm{GeV}~(hadr.) \\ \sigma(10~\mathrm{GeV}) \approx 1~\mathrm{GeV}~(EMC) \\ \sigma(m_Z) \approx 2~\mathrm{GeV}~(Tevatron) \end{array}$$

  $\rightarrow$ Fitted approx. shape $\sigma(Q) = 2.1 Q/(7+Q)$GeV

- Recoils : along colour neighbours (or chain of neighbours) or onto all initiators and beam remnant partons equally. (k_z rescaled to maintain energy conservation.)

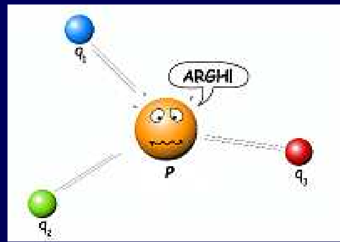
(...) $\otimes$ Hadronization.

- Imagine placing a stick o' dynamite inside a proton, imparting the 3 valence quarks with large momenta relative to each other.

'Ordinary' colour topology

(e.g. $Z^0 \to q\bar{q}$):

'Baryonic' colour topology

(e.g. 

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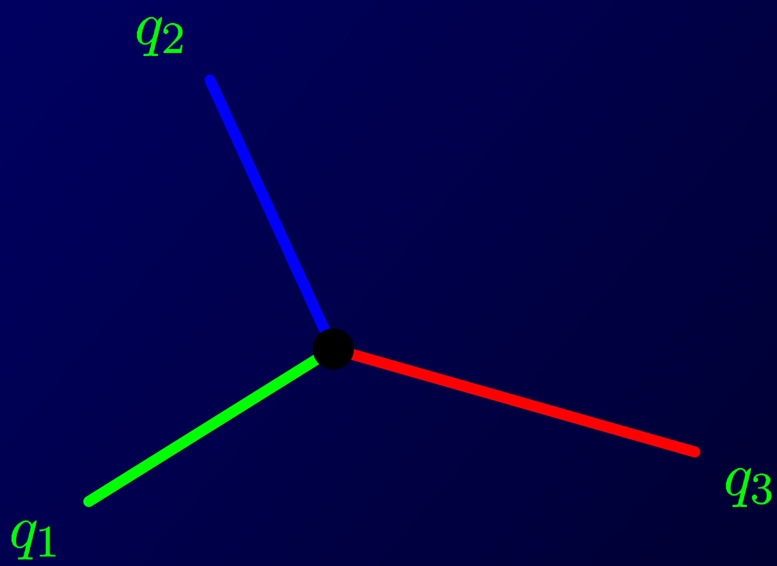


- How does such a system fragment? How to draw the strings?

(Junction Fragmentation)

How does the junction move?

- A junction is a topological feature of the string confinement field: $V(r) = \kappa r$. Each string piece acts on the other two with a constant force, $\kappa \vec{e}_r$.
- $\Longrightarrow$ in junction rest frame (JRF) the angle is 120° between the string pieces.
- Or better, 'pull vectors' lie at 120°:

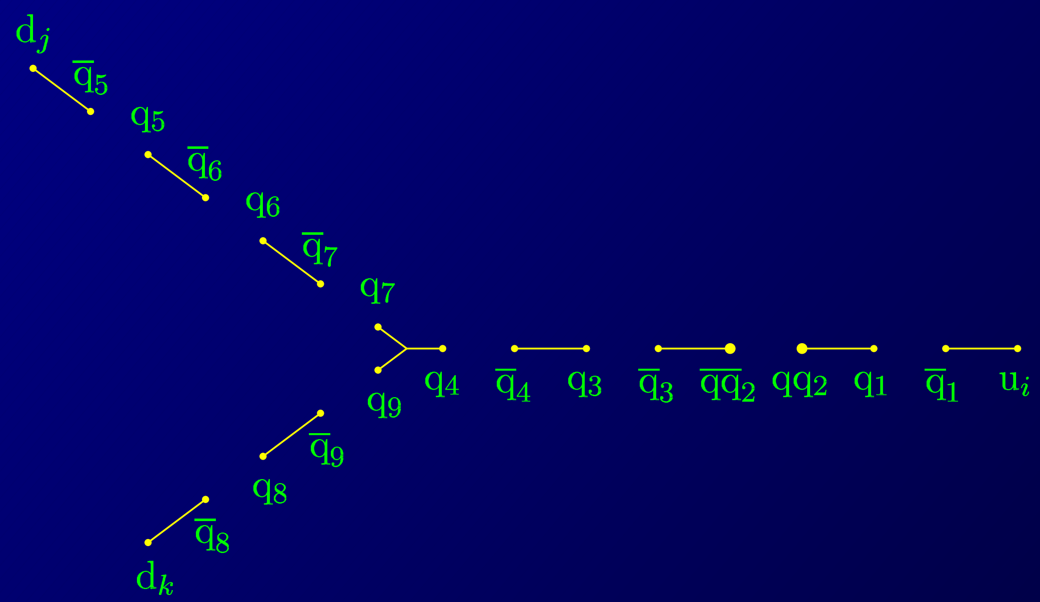
$$p^\mu_{\mathrm{pull}} = \sum_{i=1,N} p^\mu_i e^{-\sum_{j=1}^{i-1} \frac{E_j}{\kappa}}$$

(since soft gluons 'eaten' by string)

- Note: the junction motion also determines the baryon number flow!)

Junction Fragmentation

How does the system fragment?

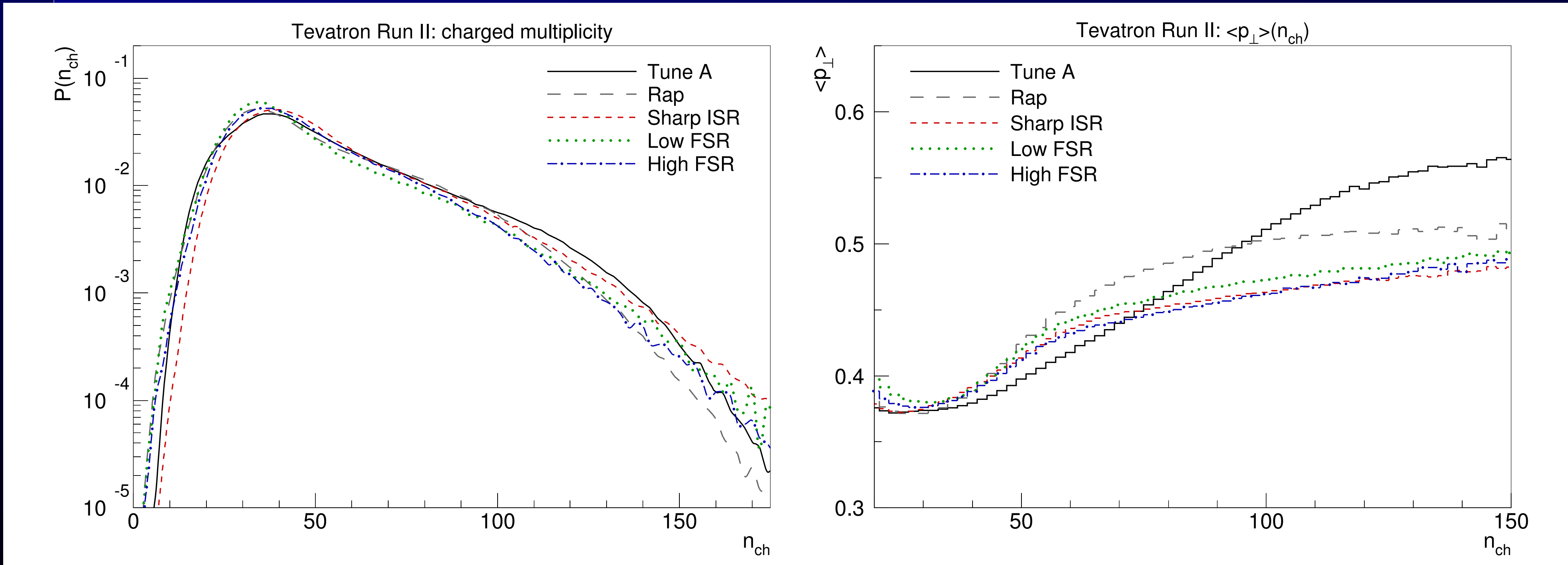


- NB: Other topologies also possible (junction–junction strings, junction–junction annihilation).

Model Tests

- 3 ‘Tune A’–like tunes at the Tevatron, using charged multiplicity distribution and $\langle p_\perp \rangle(n_{\mathrm{ch}})$, the latter being highly sensitive to (poorly understood) colour correlations.
- Similar overall results are achieved (not shown here),

but $\langle p_\perp \rangle(n_{\mathrm{ch}})$ still difficult!



Colour Correlations:

Currently, this is the biggest question.

- Tune A depends on VERY high degree of (brute force) colour correlation in the final state.
- Several physical possibilities for colour flow ordering investigated with new model. So far it has not been possible to obtain similarly extreme correlations.
- This may be telling us interesting things!

More studies are still needed... in progress.

- Fortunately, this is not a showstopper. Mostly relevant for soft details (parton $\leftrightarrow$ hadron multiplicity etc).

Outlook

- To fully exploit expected experimental precision, need good understanding of (all aspects of) hadron collisions.
- We've developed a new UE/PS model including:
  $p_\perp$–ordered *interleaved* parton showers and multiple interactions, correlated remnant parton distributions, impact parameter dependence, extended (junction) string fragmentation model, etc.
- We even made it available! $\rightarrow$ PYTHIA 6.3
- Good overall performance, though still only primitive studies/tunes carried out (except for FSR).
- Colour correlations still a headache.

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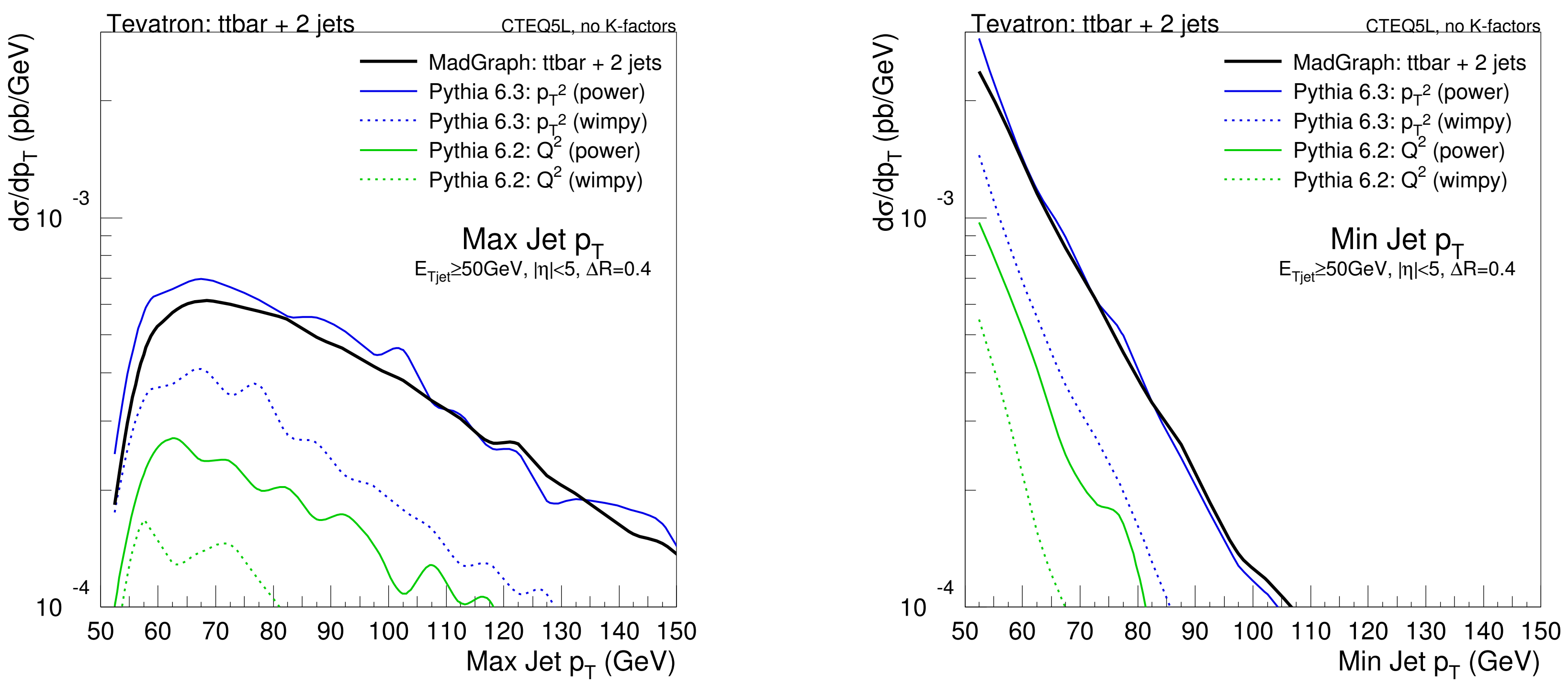

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